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Integrated Launch Package Design With Considerations for Reduced Scale Demonstration

Alexander E. Zielinski

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Alexander E. Zielinski
Weapons & Materials Research Directorate

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Abstract

The design of an integrated launch package for an electromagnetic rail gun is considered. A code that incorporates analytical engineering expressions for thermal and mechanical loads was used. The armature linear current density and armature and rail pressures are used to define the range of solutions, based on mission requirements and sub-projectile criteria. Characteristics for large and reduced scale launcher and integrated launch package (ILP) solutions are presented, which are consistent with mission requirements. Additionally, a cursory examination of augmented rail guns for ILP feasibility is presented.

ACKNOWLEDGMENTS

This assessment was supported by LTC Tanner, Electromagnetic Gun Program Manager for the U.S. Army Research Laboratory (ARL). LTC Tanner also provided a careful technical review of this manuscript. Several helpful discussions were conducted with the Launcher Working Group, co-chaired by Mr. Francis Stefani, Institute for Advanced Technology (IAT), and included Drs. Jerome Tzeng and Jim Newill (ARL), Mr. Eric Kathe, Benet Weapons Laboratory, and Dr. Ian McNab and Mr. Trevor Watt, IAT. Also, significant practical guidance in launcher and armature design was provided by the Focused Technology Program Barrel Panel (1998), chaired by Dr. Keith Jamison, Science Applications International Corporation. Panel members included Mr. Dave Bauer, IAP Research Inc., Mr. Raymond Zowarka, University of Texas, Center for Electromechanics, and Dr. Jerald Parker, IAT.

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1. Introduction

A simple electromagnetic railgun is comprised of two parallel conductors and two orthogonal insulators. Current is conducted in a rail, passes through another conductor placed between the rails (and free to move), and returns through the other rail. The moving conductor can be gaseous or solid and is called the armature. Typically, the rails are fabricated from copper, and the armature is solid and fabricated from aluminum. The geometry of the rail conductors mainly determines the inductance gradient (L′)—essentially the amount of force per unit current squared applied to the armature.

A numerical approach was adapted for the assessment undergoing consideration. A code that incorporates analytical engineering expressions for thermal and mechanical loads was used to design integrated launch packages (ILPs) for both simple and augmented railguns [1, 2]. Resultant launcher dimensions and ILP properties (mass and dimensions) are calculated for each type of railgun. The topology of the armature is derived from existing, successful experiments when high-density tungsten-alloy penetrators were launched with a single taper sabot [3, 4]. A double taper sabot was also successfully employed in the presence of armature contact transition, where the bore cross section had an aspect ratio greater than two [5]. The type of armature used in these investigations is called a "C"-shaped armature or trailing arm armature.

The issue of energy transferred from a pulsed power source to a railgun breech is not addressed in this study. Note that some pulsed power supply topologies have internal characteristics that may be more amenable to coupling to higher impedance loads (e.g., augmented railguns, series-stacked rails) and could offer additional system benefits. Also, recovering barrel magnetic energy at projectile exit with a muzzle shunt device, particularly with an augmented launcher, may place additional constraints on ILP launch dynamics, and they are not addressed in this report either.

2. Engineering Models for the Launcher and ILP

The launch velocity (V_f) and muzzle energy are specified as mission requirements, and from that information, the total launch mass is determined

(M_{tot}). For the full-scale ILP, the rod diameter is scaled to the cubed root of the sub-projectile flight mass for a conventional 120-mm kinetic energy penetrator [6]. A 120-mm tank-cannon round (1800 m/s with electrothermal chemical propulsion, 22-mm rod diameter, and 5.1-kg flight mass) scaled to the full-scale Phase 2 ILP requirement (11-MJ, 2500-m/s, 6-m launcher) results in a diameter of 16 mm. A prior launch package effort used a rod diameter of 19 mm [4]. A rod diameter of 18 mm was selected for this assessment.

For a sinusoidal current pulse with the half-cycle selected to coincide with projectile exit from the launcher (X_f), the peak current is determined as

$$I_{pk} = V_f \sqrt{\frac{2M_{tot}}{L'X_f}} \tag{1}$$

The ratio of the peak-to-average acceleration (δ) is 2 and is a conservative value for rotating machines that provide pulsed power to a railgun load. For example, multi-phase rotating machines can provide peak currents that are roughly 20% lower than those calculated for a sinusoidal current pulse (δ < 2). Furthermore, trapezoidal current waveforms with aggressive rise and fall times (< 0.5 ms) produce peak currents that are at best 30% lower than those calculated for a sinusoidal current waveform [7].

The peak current establishes the peak axial acceleration, and the penetrator's material properties (i.e., strength to density ratio, Y_p / ρ_p) determine the unsupported rod length as

$$l_e = \frac{0.7Y_p}{\rho_p a_{pk}}, \tag{2}$$

in which the factor 0.7 accounts for a margin of safety. The minimum current-carrying cross-sectional area (i.e., for the armature) is determined from the mission requirements as

$$A_{\min} = \sqrt{\frac{2M_{tot}V_f}{GL'}} \tag{3}$$

in which G is the action integral constant and implicitly determines the temperature rise of the (aluminum) armature conductor (18,000 A^2-s/mm^4 ~ 400° C). A limiting value of 20,000 A^2-s/mm^4 has been found experimentally [8]. Specifying an armature length of 1.5 calibers (when 1 caliber = rail height [h_r]) has been found to yield adequate mechanical compliance for "C"-shaped armatures.

The mass of the unsupported rod lengths, the armature length used to transfer current from the rails, and front bourrelet are subtracted from the total mass. This remaining mass (ΔM) can be used to determine the partition between the aluminum sabot and supported tungsten rod section. Using conditions for matching the strain between the sabot (subscript "*s*") and penetrator (subscript "*p*") gives the supported length as **[9]**

$$l_f = \beta^{-1} \ell n \left[\frac{\beta \Delta M}{A_p \rho_p} + 1 \right] \tag{4}$$

in which

$$\beta = \frac{E_p \rho_s}{E_s \rho_p} \frac{\rho_p a_{pk}}{Y_p}. \tag{5}$$

The cross-sectional area of the sabot to support the rod is

$$A_s = A_p \frac{\rho_p}{\rho_s} (e^{\beta l_f} - 1) \tag{6}$$

and the sabot height follows as

$$h_s = \frac{A_s + A_p}{s}. \tag{7}$$

Initially, the height of the sabot (h_s) is taken to be the height of the rail (h_r). The equations are iterated so that solutions in which $\Delta M > 0$ are found for $h_s < h_r$, essentially by incrementing the rail-to-rail spacing, *s*.

The breech energy is computed by adding the muzzle kinetic energy and the sum of the ohmic losses. The ohmic losses are found by multiplying the action integral

$$\left(\frac{2\, M_{tot} V_f}{L'} \right)$$

by the various resistive terms for the armature bulk and contact and rails. Because the sinusoidal current pulse is defined to be zero at projectile exit, the magnetic energy stored in the launcher is zero. Assessment of launcher efficiency for non-zero exit current has been addressed and, for today's launcher and armature technology, was found not to be the dominant contributor to launcher energy losses **[10]**.

The model for the contact voltage is taken from experimentally measured solid armature data **[3]**. These data are for a solid armature launching a tungsten alloy rod with a single taper, "C"-shaped armature to a velocity of 2350 m/s. The data are fit as a function of the velocity (v) as

$$V_c = V_{co} e^{+\frac{v}{v_t}} \tag{8}$$

in which $V_{co} = 0.7$ V and $v_t = 362$ m/s.

The bulk armature resistance is computed from the dimensions of the bore and a resistivity corresponding to 400° C (roughly 80 nΩ-m).

The thickness of the rail is estimated by assuming that one-half the muzzle kinetic energy is deposited in the full length of rail conductor with a bulk temperature rise of 75° C. The inductance gradient is computed with the two-dimensional cross section of the rails [11].

The resistance of the rails (R) is computed from an approximation found to be in very good agreement with medium caliber launchers [12]. However, the approximation under-predicted the resistance for larger caliber launchers and was modified as

$$R = (2.5)\frac{\rho_r X_f}{A_r} \tag{9}$$

in which the full cross-sectional area of the rails is A_r and the resistivity of the (aluminum alloy) rails is ρ_r.

Lethality (e.g., armor penetration at range) is not specified. However, requirements such as the ratio of the sub-projectile length to diameter ($l/d \geq 20$) and ILP parasitic mass (≤ 50%) are used to guide the ILP and launcher solutions.

A flow diagram for the calculations is illustrated in Figure 1. Values are assumed for the rail height and bore aspect ratio (s/h_r) and are incremented. The output data are then assessed for various aspect ratios (s=1, 1.4, and 3) as a function of rail height. In previous work, the height of the armature was equal to the sabot height but less than the rail height to allow mechanical support at the rail-insulator interface [13]. For the present work, a finned rail configuration is assumed that allows the armature height to be equal to the rail height [14]. However, the sabot height is less than the armature height. Furthermore, physical parameters are used to constrain the number of solutions. For example, solutions in which the bore pressure is greater than 100 ksi are not written to the output file. A summary of the constraints is listed in Table 1.

Table 1. Summary of Physical Constraints

Parameter	Constraint
Bore Pressure	< 100 ksi
Flight l/d	< 40
Armature Height	= Rail Height
Axial Electrical Conduction	= 1 Transient Skin Depth
Rod Diameter	< Armature Height
Rod Diameter	< One-half the Rail Spacing
Sabot Height	< Rail Height
Rod-Sabot Interface Shear Stress	< 55 ksi

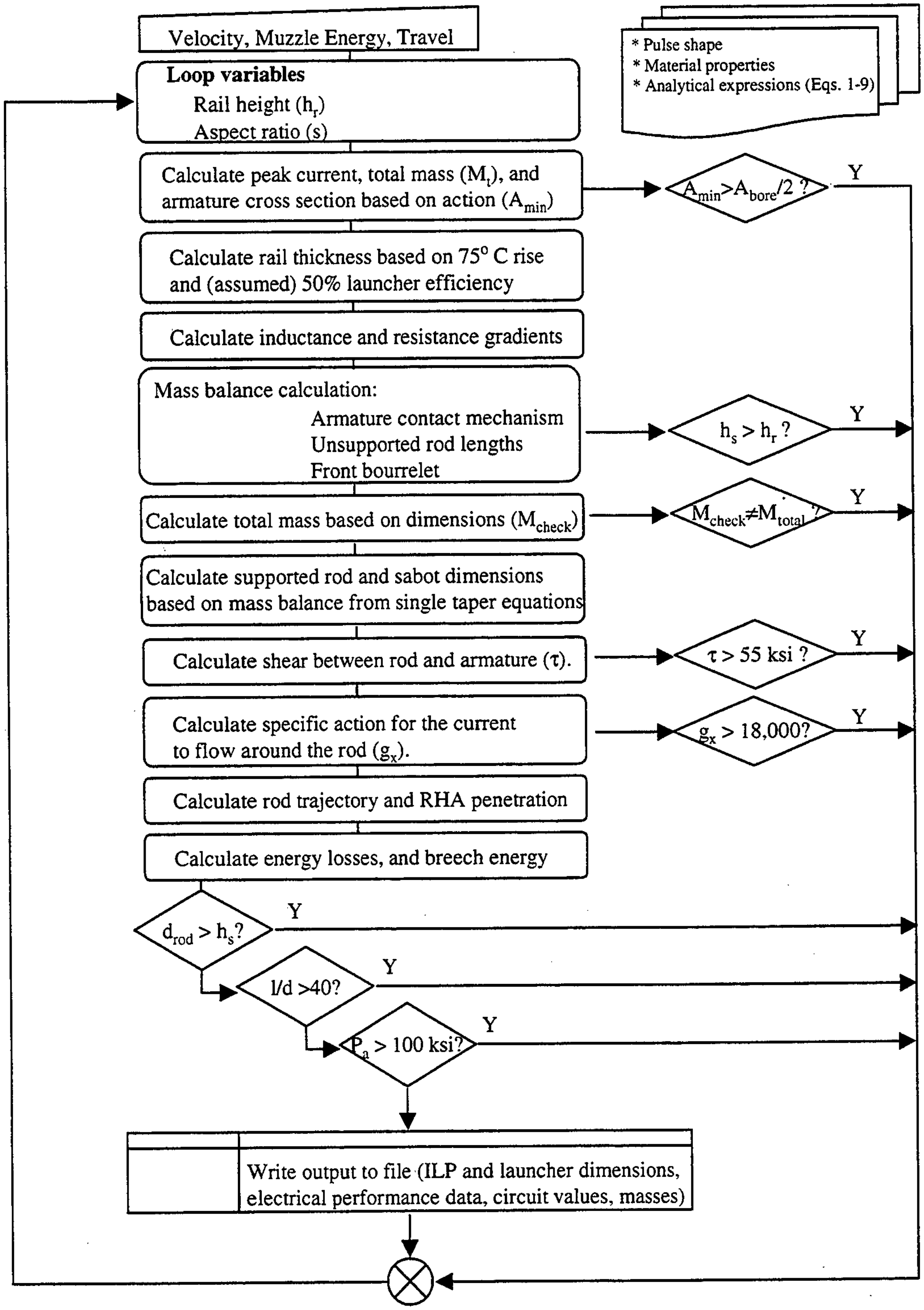

Figure 1. Flow Diagram for Calculations.

3. Non-augmented Railgun

Output data from the model include launcher electrical efficiency, launch package useful mass fraction, breech energy, peak (sinusoidal) current, and bore aspect ratio. Engineering parameters such as rail pressure, armature (base) pressure, and armature linear current density can be used to define the bore dimensions.

These three parameters have been found useful in the design of armatures and railguns **[15, 16, 17, 18]**. As such, values that represent challenging designs and in some limited capacity have been experimentally demonstrated, are also indicated relative to the output data. The challenging design values indicated in Figures 2 through 4 have been increased (by 15% for those parameters that are proportional to the current and 30% for those parameters that are proportional to the current squared) to be consistent with the rather conservative, assumed sinusoidal current waveform. The engineering criteria are listed in Table 2.

Table 2. Criteria Used in Launcher and Armature Design

Engineering Parameter	Maximum Value (scaled to peak sinusoidal current)
Armature Linear Current Density (kA/mm)	43 (50)
Armature (base) Pressure (ksi)	49 (70)
Rail Pressure (ksi)	34 (48)

In general, nearly all parameters improve as the aspect ratio increases; the exception is useful mass fraction. Figure 2 shows the rail pressure. The entire design space is found to be less than the aforementioned challenging design value.

Figure 3 shows the armature pressure. While all values for rail height produce acceptable designs, the aspect ratio should be larger than 1 for the pressure to remain below the challenging design value.

Figure 4 shows the armature linear current density, which is found to decrease as the rail height increases. Acceptable designs are produced for rail heights greater than 61 mm.

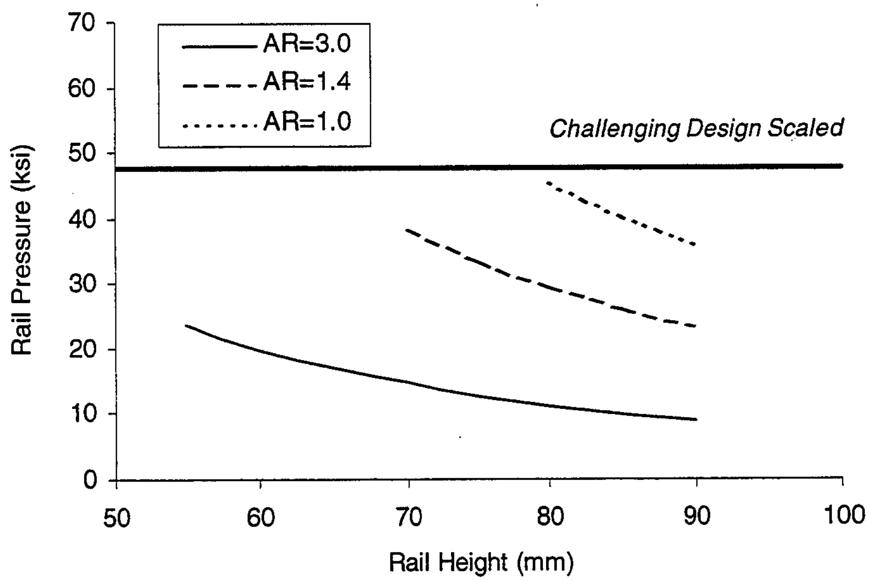

Figure 2. Rail Pressure as a Function of Rail Height.

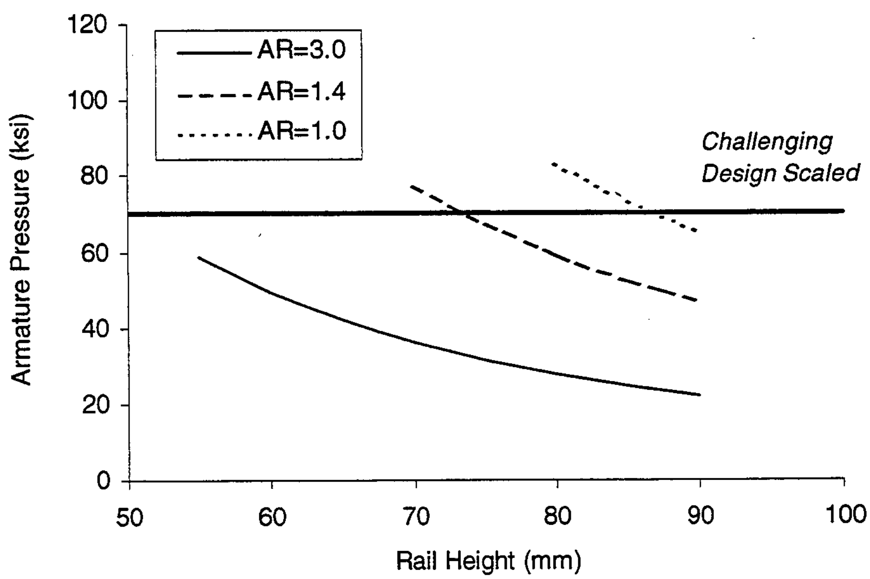

Figure 3. Armature (Base) Pressure as a Function of Rail Height.

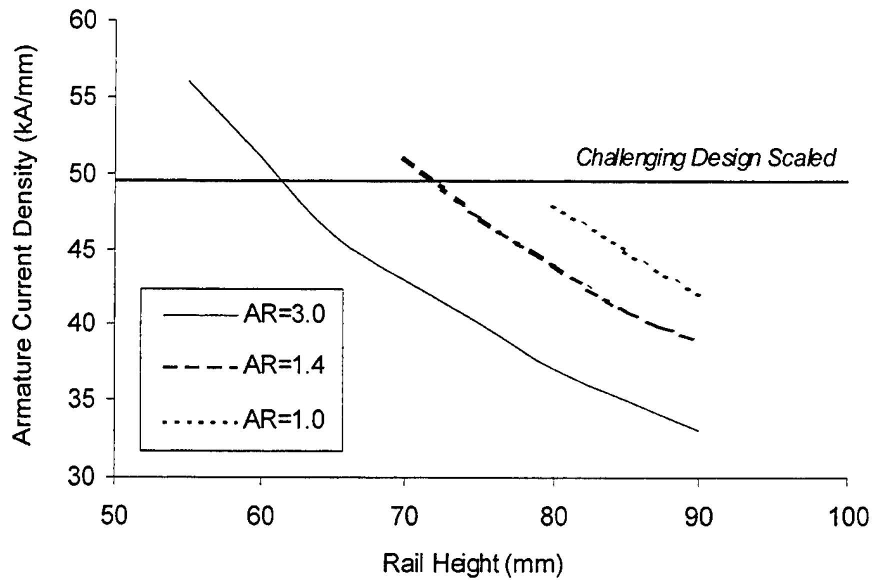

Figure 4. Armature Linear Current Density as a Function of Rail Height.

In addition to maintaining a design that produces values that are below the three requirements, it is also useful to consider the system efficiency (defined by the launcher and ILP in this report). Figure 5 shows the useful energy, calculated from the subprojectile mass and launch velocity. Since all designs are for a launch velocity of 2500 m/s, the decrease in useful mass is a result of the bore cross section not fully used for the materials assumed (aluminum armature and sabot and tungsten subprojectile). Additionally, by selecting a smaller rail height, one can achieve the same useful energy at a larger aspect ratio as was achieved at a low aspect ratio. Although not illustrated, the larger aspect ratio then provides for a potentially smaller barrel mass.

Figure 6 shows the breech energy required to achieve the Phase 2 requirements. The breech energy is found to be roughly constant as a function of rail height. However, substantial reduction can be achieved for large aspect ratios.

Finally, Figure 7 illustrates the system efficiency (the "system" is defined here for the launcher and ILP only). It can be seen that while the larger aspect ratio case produced relatively less useful energy compared to the smaller aspect ratio case for the same rail height, the appetite for more breech energy clearly implies a small rail height and large aspect ratio solution.

Using Figures 2 through 7, one can ascertain the range of feasible solutions for a 2500-m/s Phase 2 ILP. A 63-mm rail height with a 2:1 aspect ratio is one choice that satisfies design criteria with the largest system efficiency.

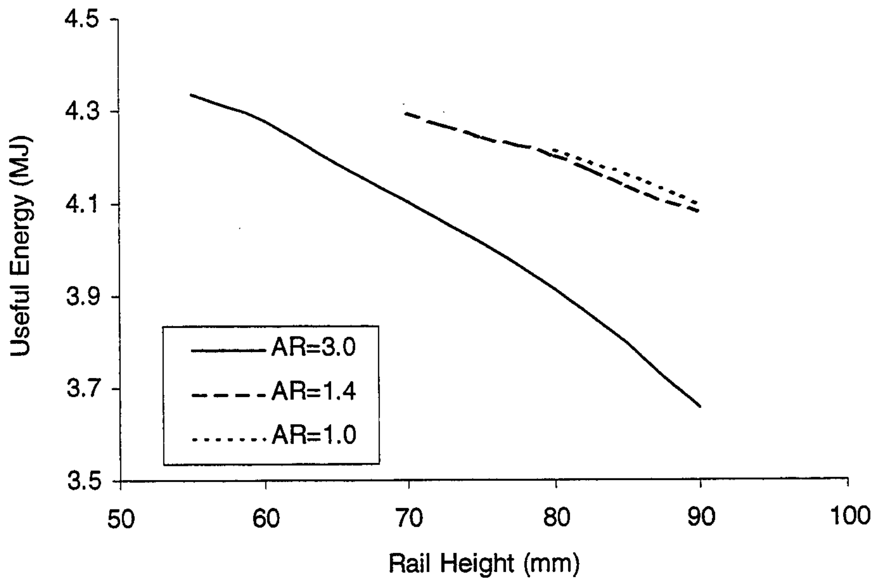

Figure 5. Useful Mass Fraction as a Function of Rail Height.

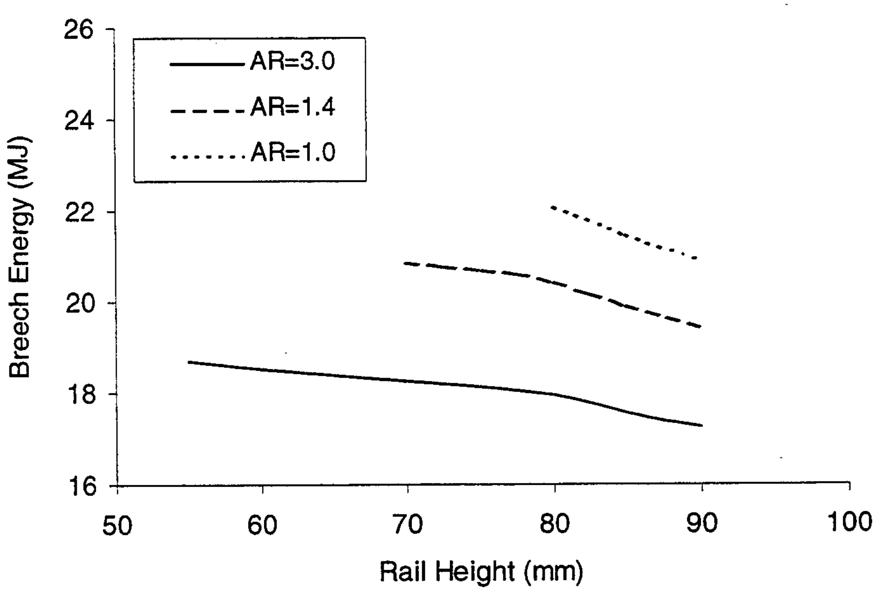

Figure 6. Breech Energy as a Function of Rail Height.

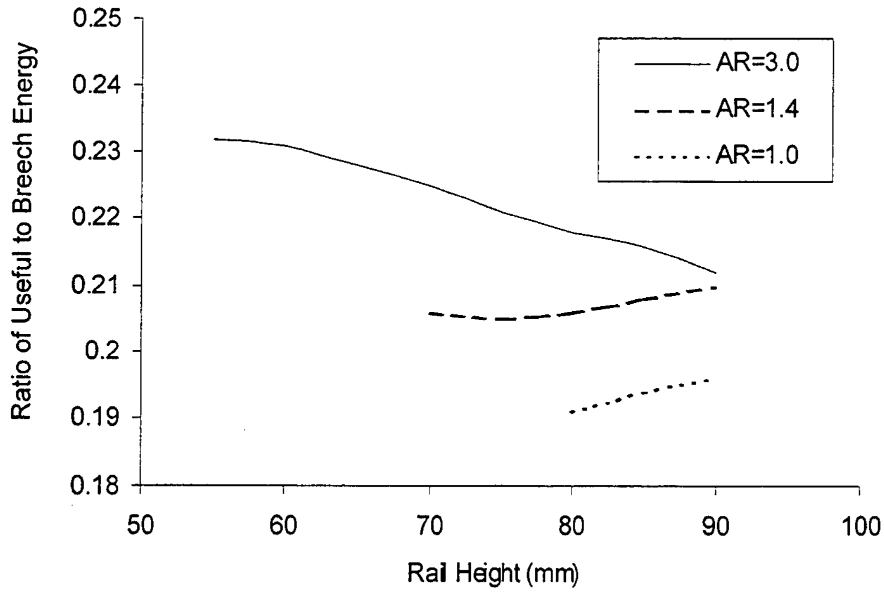

Figure 7. System Efficiency as a Function of Rail Height.

Note that the computations used to construct the curves in Figures 2 through 7 are not for a single sub-projectile design. Bore size and structural and thermal loads are used to determine the sub-projectile length and parasitic mass (which is not specified or constant). An illustration of the ILP and bore cross section for the Phase 2 ILP requirements is shown in Figure 8. Characteristics are summarized in Table 3.

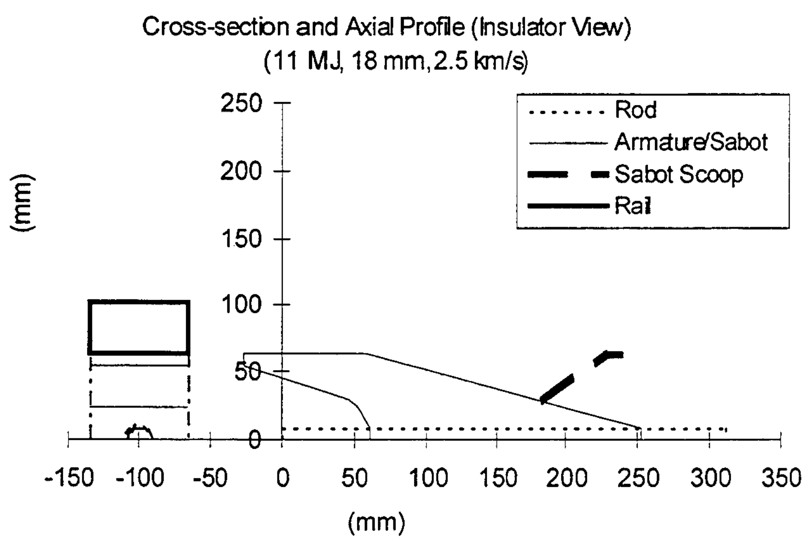

Figure 8. Illustration of Phase 2 ILP and Launcher Cross Section.

4. Reduced Scale Demonstration of Phase 2 ILP Parameters

In a research program, it is often pragmatic to demonstrate characteristics representative of the full-scale device (i.e., Phase 2 ILP) at reduced scale. This approach affords rapid evaluation at reduced cost. The drawback is that phenomena associated with electromagnetic acceleration may not fully scale to larger launchers. The aforementioned engineering code includes a few of the limiting, nonlinear thermal and structural loads and is therefore amenable to calculations at reduced scale.

Curves similar to Figures 2 through 4 can be generated with the approach discussed in Section 2. The principal characteristics presented in Table 3 for the armature linear current density and rail and armature pressures can be used as operating conditions for a reduced scale ILP launched with 2 MJ of total muzzle energy in 3 m of travel. In order to offer the opportunity to examine implications of a high aspect ratio bore, the bore aspect ratio for the reduced scale demonstration was selected as 2:1. Also, with the scaling presented in Section 2, the rod diameter is 8.8 mm. Figures 9 through 11 illustrate the variation of the critical engineering parameters with rail height. Exit velocities of 2300 m/s and 2500 m/s are shown. In order to be consistent with the Phase 2 ILP, a rail height of 38 mm is appropriate.

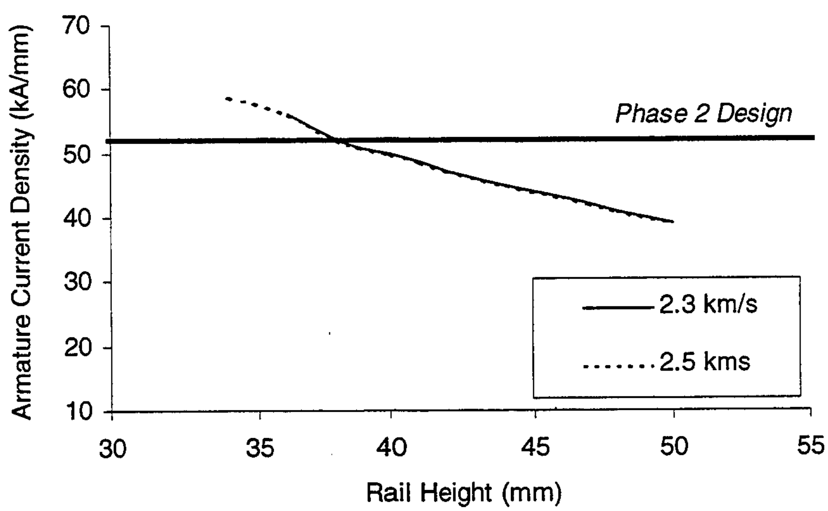

Figure 9. Armature Linear Current Density as a Function of Rail Height.

Table 3. Characteristics for a Single Taper Phase 2 ILP and 6 m Travel

Muzzle Kinetic Energy (MJ)	11		
Launch Velocity (m/s)	2500		
Launcher Parameters			
Peak (Sinusoidal) Current (MA)	3.3	*Peak Multiphase Current (MA)	2.9
Rail Height (mm)	63.0		
Core Aspect Ratio	2.0		
Rail Spacing (mm)	126.0		
Rail Thickness (mm) for 75 C	43.4		
Axial Inductance Gradient (μH/m)	0.67		
Lateral Inductance Gradient (μH/m^2)	2.39		
Rail Resistance Gradient (μΩ/m)	22.8		
Rail Pressure (ksi)	29.6	Scaled to Peak Multiphase Current	23
ILP Parameters			
Armature Height (mm)	63.0		
Sabot Height (mm)	52.0		
Armature Aspect Ratio	2.0		
Minimum Armature Thickness (mm)	19.1		
Crossover Action (% Maximum)	75		
Armature Action Integral (GA^2-s)	26.1		
Armature Linear Current Density (kA/mm)	52.4	Scaled to Peak Multiphase Current	46
Base Pressure (ksi)	67.0	Scaled to Peak Multiphase Current	52
Peak Acceleration (kgees)	106	Scaled to Peak Multiphase Current	82
Dimensions			
Unsupported Rod Length (mm)	57	Rod Diameter (mm)	18
Supported Length (mm)	200	Rod Length (m)	0.32
RHA Penetration at 4 km (m)	0.41	*l/d*	18
Mass Budget			
Unsupported Rod Ends (kg)	0.51	Contact Mechanism (kg)	0.62
Front Bourrelet (kg)	0.24	Rod (kg)	1.38
Sabot (kg)	1.27	Total ILP (kg)	3.52
Discarded (kg)	2.13	Useful Mass Fraction (%)	40
Energy Allocation at Half-Cycle (4.8 ms)			
Rails (MJ)	3.6	Armature Contacts (MJ)	1.1
Bulk Armature (MJ)	0.34	Breech Energy (MJ)	16.1
Energy Distribution (%)			
Rails	22	Inductive	0
Armature (Total)	10	Kinetic	68

*For a 1-ms rise and fall time (δ = 1.4)

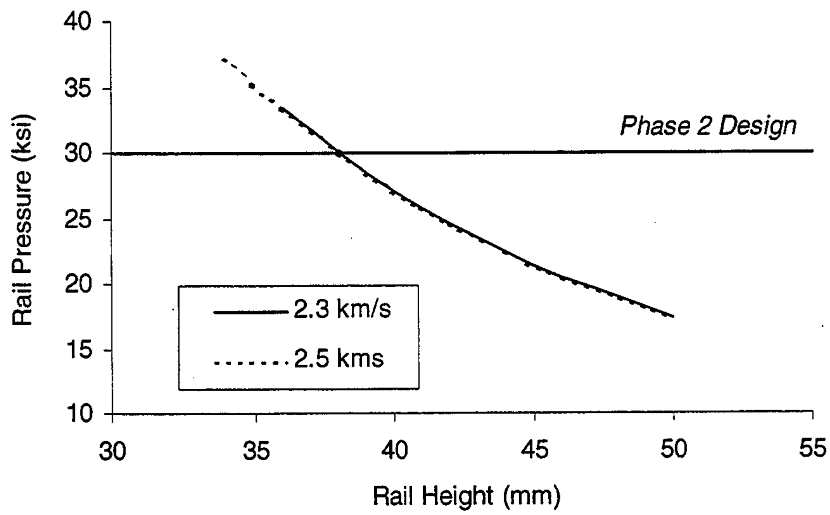

Figure 10. Rail Pressure as a Function of Rail Height.

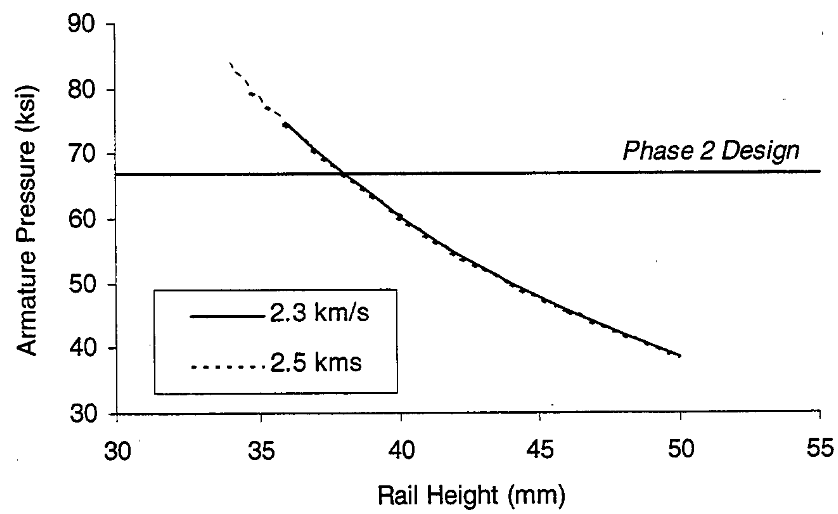

Figure 11. Armature (base) Pressure as a Function of Rail Height.

While the engineering criteria are met for the reduced scale demonstration, the 2500-m/s exit velocity requirement forces reduced ILP performance defined by the useful mass fraction and subprojectile *l/d*. A better solution, which provides for a more meaningful medium caliber demonstration while simultaneously satisfying the remaining requirements, is for a 2300-m/s exit velocity and a slightly larger diameter rod (9.75 mm). Characteristics for a reduced scale ILP with an exit velocity of 2300 m/s, 3 m of travel, and a 9.75-mm diameter rod are listed in Table 4.

Table 4. Reduced Scale Single Taper ILP, 3 m of Travel, and 9.75-mm Rod Diameter

Muzzle Kinetic Energy (MJ)	2		
Launch Velocity (m/s)	2300		
Launcher Parameters			
Peak (Sinusoidal) Current (MA)	2.0	*Peak Multiphase Current (MA)	1.7
Rail Height (mm)	38		
Core Aspect Ratio	2.0		
Rail Spacing (mm)	76		
Rail Thickness (mm) for 75 C	26.1		
Axial Inductance Gradient (μH/m)	0.67		
Lateral Inductance Gradient (μH/m^2)	3.96		
Rail Resistance Gradient (μΩ/m)	63		
Rail Pressure (ksi)	29.6	Scaled to Peak Multiphase Current	22
ILP Parameters			
Armature Height (mm)	38		
Sabot Height (mm)	28		
Armature Aspect Ratio	2.0		
Minimum Armature Thickness (mm)	14.1		
Crossover Action (% Maximum)	69		
Armature Action Integral (GA^2-s)	5.2		
Armature Linear Current Density (kA/mm)	53	Scaled to Peak Multiphase Current	46
Base Pressure (ksi)	67	Scaled to Peak Multiphase Current	50
Peak Acceleration (kgees)	180	Scaled to Peak Multiphase Current	134
Dimensions			
Unsupported Rod Length (mm)	34	Rod Diameter (mm)	9.75
Supported Length (mm)	124	Rod Length (m)	0.19
RHA Penetration at 2 km (m)	0.24	*l/d*	20
Mass Budget			
Unsupported Rod Ends (kg)	0.087	Contact Mechanism (kg)	0.164
Front Bourrelet (kg)	0.089	Rod (kg)	0.248
Sabot (kg)	0.253	Total ILP (kg)	0.756
Discarded (kg)	0.507	Useful Mass Fraction (%)	33
Energy Allocation at Half-Cycle (2.6 ms)			
Rails (MJ)	0.975	Armature Contacts (MJ)	0.232
Bulk Armature (MJ)	0.090	Breech Energy (MJ)	3.3
Energy Distribution (%)			
Rails	29	Inductive	0
Armature (Total)	10	Kinetic	61

*For a 0.25-ms rise and fall time (δ = 1.2)

Figure 12 shows an illustration of the ILP and bore cross section for demonstration of Phase 2 ILP requirements at reduced scale.

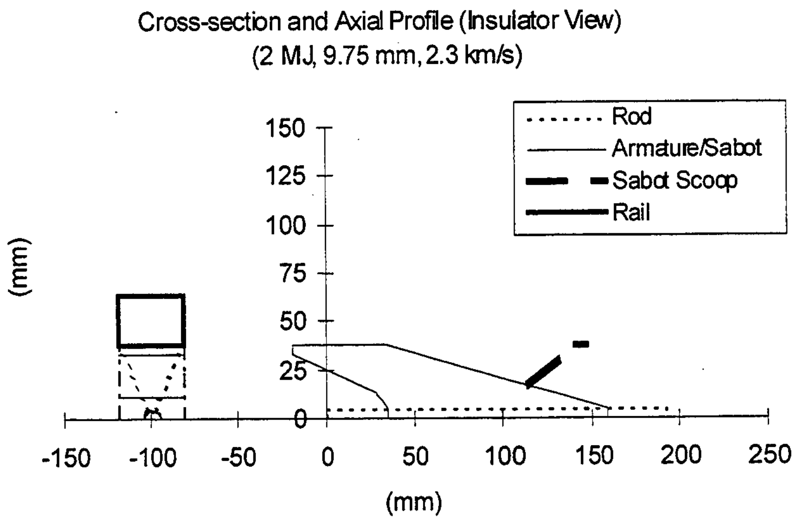

Figure 12. Illustration of Reduced Scale Single Taper ILP and Launcher Cross Section.

5. Summary and Conclusions

A single taper, "C"-shaped armature configuration, which has launched the most tactically viable sub-projectiles to date, is assumed throughout this assessment. A bore cross section and dimensions for an ILP were identified, which can be engineered to achieve less than 50% parasitic mass, *l/d* greater than 20, 11 MJ total muzzle energy, and 2500 m/s in 6 m of travel. The bore has a rectangular cross section, 63 by 126 mm. Additionally, a reduced scale launcher was identified that achieves critical engineering parameters necessary to demonstrate Phase 2 ILP performance. These parameters are also demonstrated in a rectangular bore (38 by 76 mm), 3 m of travel, and an exit velocity of 2300 m/s. Relaxing input conditions and assumptions, such as barrel length and armature topology, will certainly provide for more flexibility in the integrated design.

Significant analysis (e.g., finite element) is needed before engineering drawings and specifications can be produced for the launcher and ILP. Detailed material selection for the rails, insulators, and containment structure is also needed. Many solutions exist to meet both the Phase 2 ILP and reduced scale demonstrations. However, this assessment (a) identifies critical ILP and launcher characteristics that satisfy the mission requirements and (b) provides a reduced scale demonstration that is on the technical path toward demonstrating those characteristics. Finally, consideration of pulsed power supply options is required to assess overall system efficiency and utility.

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APPENDIX A

AUGMENTED RAILGUN ASSESSMENT

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AUGMENTED RAILGUN ASSESSMENT

A-1 Augmented Railgun

The inductance gradient can be increased by altering the conductor topology or, for the case of interest here, by augmenting the field produced by the rail conductors. Augmenting the field can be accomplished very simply by placing permanent magnets along the length of the launcher; for this investigation, placing conductors that carry current close to the bore is considered. Perhaps the most practical configuration is when the conductors forming the turn are electrically in series with the rails (i.e., the rail current is equal to the turn current). For the same accelerating force, the current and therefore the thermal load, can be reduced by using an augmented railgun. The augmenting turn is fabricated from copper, and thus, one penalty for increased L′ is increased ohmic losses.

The issues associated with augmentation involve a trade-off between benefit and burden. Reduced armature mass is a clear benefit. However, other system-oriented benefits include

- Reduced current at breech and cable connections
- Reduced current through switching devices
- Reduced rail damage

Burdens associated with augmentation include

- Increased in-bore and external electromagnetic environment
- Launcher mass and containment complexity
- Increased breech voltage

With the aforementioned design methodology, the inductance gradient was increased to simulate augmentation. The cost of augmentation is the resistivity of the conductor that comprises the augmenting turn. An empirical approach that uses data for a well-designed augmented launcher [1] is chosen to represent the augmenting turn resistance per unit length and is given as

$$R'_{turn} = \frac{500\mu\Omega}{m}\left[\frac{17mm}{h_r}\right]. \tag{1}$$

Similarly, the augmented inductance gradient is found from

$$L'_{aug} = (2.25)L' \tag{2}$$

Essentially, the relatively low value of resistance in the turn is achieved at the expense of less than ideal coupling (i.e., 3 vs. 2.25) of the turn and bore fields with the use of a copper alloy conductor. It is assumed that the dimensions to obtain R'_{turn} are scaled inversely proportional to the rail height. In this manner, the relative proportions of the rail and turn conductors are maintained.

A-2 Railgun Comparisons

Railguns with the same bore dimensions are compared for regular and augmented designs. A figure of merit (α) is defined as the ratio of percent increase in breech energy to the percent increase in useful energy. Breech energy includes the ohmic dissipations from the armature, rail, and, when appropriate, augmenting turn. The useful energy is the amount of kinetic energy in the penetrator.

For $\alpha > 1$, the additional amount of electrical energy is far greater than the reduction in armature mass. While this condition is not efficient, it may provide some relief for system components alluded to earlier, including breech connections, switching devices, and cables. It is most desirable to achieve $\alpha < 1$; $\alpha = 1$ is termed "break even." In all cases, it must be remembered that augmentation requires additional delivered electrical energy.

Shown in Figure A-1 is α as a function of rail height for the 11-MJ Phase 2 ILP conditions at a rail spacing that just provides for a valid solution. It can be seen that, in general, higher launch velocity yields a more efficient use of the augmenting turn because of the combined inherent shorter pulse width and larger peak current that provides for subsequent lower ohmic losses. Also, α approaches break even for very large rail heights. Unfortunately, system efficiency is generally less for large rail heights. Figure A-1 indicates that for the Phase 2 ILP, there is no ILP-based benefit for augmenting the launcher. Alternatively, no penalty is imposed on the ILP either.

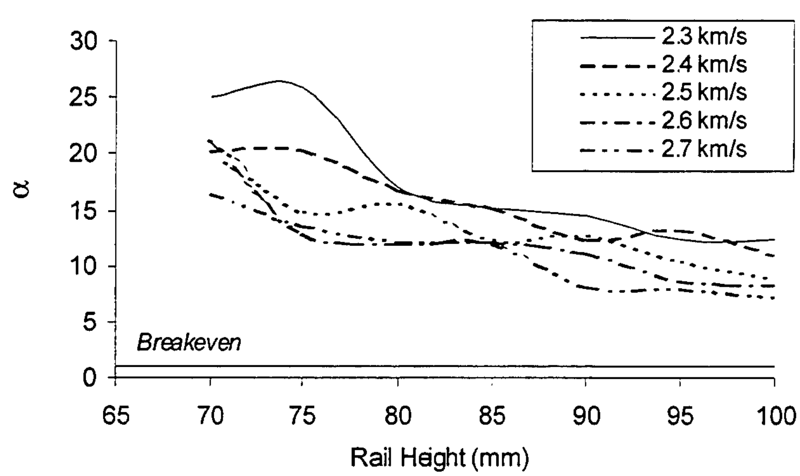

Figure A-1. α For the Phase 2 ILP (11 MJ).

Augmentation generally produces a minimum rail height a few millimeters larger than for a non-augmented railgun. Additional calculations, in which the smallest (but not equal) rail spacings are used to assess α, yield values that are less than half those values indicated in Figure A-1. However, the trend is the same as indicated in Figure A-1.

Augmentation has been used successfully and it is instructive to assess those conditions that yield usefulness [2, 3]. Smaller values for muzzle energy and ILP travel were selected (2 MJ, 0.6 MJ and 3 m, 2 m) and values for α were generated. The figure of merit is shown in Figure A-2 for a velocity of 2500 m/s. The shaded image indicates the approximate design space created by the three curves.

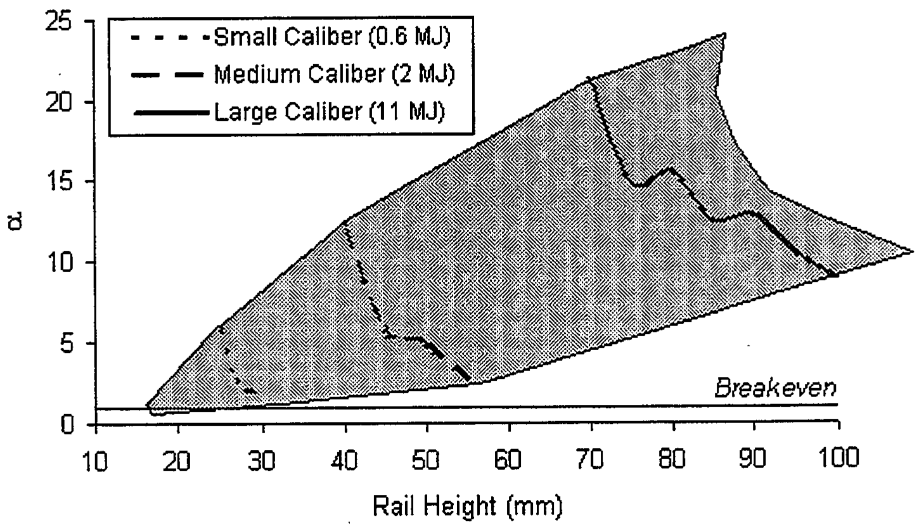

Figure A-2. α For a Wide Range of Muzzle Kinetic Energy (V_f= 2500 m/s).

The plot indicates a trend that augmentation could be advantageous for rail heights less than 30 mm and 0.6 MJ of muzzle energy. Also, given the slope of the curves and unequal bore cross sections for calculating α, it is likely that, with further detailed electromagnetic analysis and system integration, rail heights and muzzle energy approaching 30 mm and 0.6 MJ, respectively, could be viable.

Another approach examines the relative increase in breech energy for an augmented launcher. The increase is shown in Figure A-3 and the trend is similar to that indicated in Figure A-2. A significant amount of additional breech energy is needed for a large scale augmented launcher. In order for augmentation to be feasible, the increase in efficiency of energy transferred from the power supply has to be at least as great as the increase in breech energy. Only a detailed design of the pulsed power components can determine if improvements in efficiency are realizable.

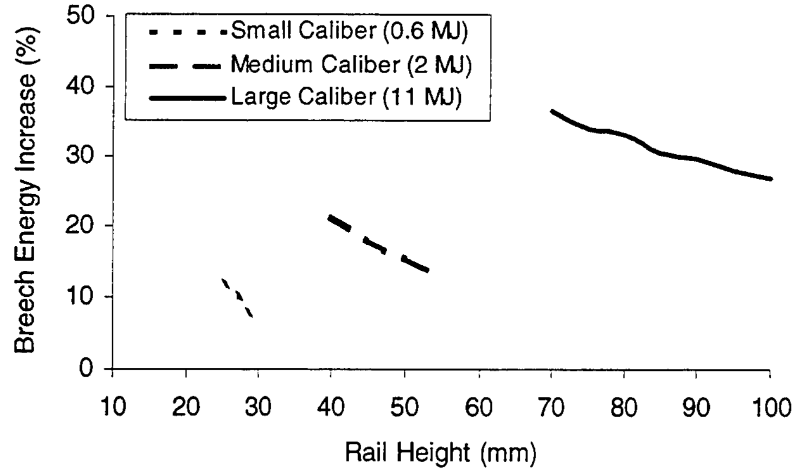

Figure A-3. Increase in Breech Energy for an Augmented Launcher (V_f= 2500 m/s).

The analyses indicate that no ILP-based advantage is obtained from augmenting a large caliber (11-MJ) railgun. Furthermore, augmentation is feasible for smaller bores and less energy. This conclusion is as expected and corroborates previously demonstrated efforts [2, 3]. Furthermore, augmenting a reduced scale launcher will not simultaneously demonstrate the engineering criteria needed to be on the path for the Phase 2 ILP demonstration. Most notably, the required peak current is less for an augmented launcher and, as expected, for the same bore aspect ratio, the armature linear current density will be far less in the reduced scale launcher than in the full-scale launcher.

Series augmentation increases the impedance of the railgun, and this may in turn increase the energy transferred from a pulsed power source to the breech. This effect was not investigated in this assessment of augmentation but can have a significant impact on the overall efficiency of the system.

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13. ABSTRACT *(Maximum 200 words)*

The design of an integrated launch package for an electromagnetic rail gun is considered. A code that incorporates analytical engineering expressions for thermal and mechanical loads was used. The armature linear current density and armature and rail pressures are used to define the range of solutions, based on mission requirements and sub-projectile criteria. Characteristics for large and reduced scale launcher and integrated launch package (ILP) solutions are presented, which are consistent with mission requirements. Additionally, a cursory examination of augmented rail guns for ILP feasibility is presented.

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